RESEARCH DEPARTMENT

SOUND LEVEL DISTRIBUTION IN CONCERT HALLS

Report No. B-063

(1955/36)

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

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SUMMARY

This report describes measurements recently carried out in five concert halls to determine the difference in sound level between the seats close to the orchestra and those at the back of the hall. The source of sound was an orchestra in all cases and measurements were made both during rehearsals and public performances.

1. INTRODUCTION.

Although the question of distribution of sound energy over the seating area of a concert hall has been studied by several observers, notably Parkin[1], who used a single loudspeaker as a sound source, it has not hitherto been of great specific interest to the B.B.C. The ability to obtain good broadcast results over a monaural microphone system has been a more important requirement than the desirability of serving all members of the audience with a fair share of the sound energy, although it has been found that halls in which microphone placing is easy are always excellent for concert-goers.

To provide a reasonable balance of energy between the front and the back of the hall, some authorities favour the use of reflectors to reflect additional energy to the back of the hall and to the back of a gallery or balcony. From experience of such halls, there is some reason to believe that reflectors may not be entirely desirable from other considerations. The ideas of specular reflection inherent in their use are only valid when the reflector (or the part being effectively used) is large compared to the wavelength of sound. The presence of a reflector is also likely to influence the effective reverberation time; this is discussed in the Appendix. Consideration of the disadvantages of reflectors makes it necessary to enquire whether their effectiveness in reducing sound level differences is in practice enough to justify their use.

In general, the sound energy in a hall can be considered in two parts, the direct and reverberant components. As an approximation it may be assumed that the level of the reverberant sound is constant over the whole auditorium, (an assumption which is, in fact, implicit in the use of all reverberation formulae), while the direct sound energy is inversely proportional to the square of the distance between the listener and the source. The level of direct sound close to the source will be higher than the reverberant, decreasing as the listener moves away until it reaches a point of equality between 20 and 30 ft from the source, and rapidly becoming a relatively unimportant component of the total energy at greater distances.

A much greater change in level with position can be expected when still close to the source than when further away. From this it follows that the extended source provided by an orchestra will give smaller reductions in level with distance than a point source. With an extended source the direct level is the resultant of a large number of components originating at varying distances from the point of observation.

When an audience is present, the reverberation time is normally reduced by virtue of the absorption associated with the audience, although in modern halls an attempt is made to reduce the difference between the full and empty hall by providing highly absorbent seats. It is to be expected, therefore, that level differences between the front and back seats will be greater when the hall is full, due to the smaller component of reverberant energy. In addition, any attenuation of the direct sound in passing over the heads of the audience will increase this effect.

2. EXPERIMENTAL TECHNIQUE.

2.1. General.

It was decided to make simultaneously, at positions close to the front and back seats respectively, a straightforward measurement of the overall integrated sound level originating from an orchestra. The possibility of measuring the direct and reverberant components directly was considered but it was not thought practicable, or particularly desirable, to separate them. It would be particularly difficult with an audience present. The overall level in any case provides interesting information and is a useful first step. This question will be discussed later.

Measurements were made in five halls, namely:

1. Royal Festival Hall, London.
2. Free Trade Hall, Manchester.
3. Philharmonic Hall, Liverpool.
4. St. Andrews Hall, Glasgow.
5. Usher Hall, Edinburgh.

The first two are examples of modern halls with reflectors, while the last two are halls of an older type with no reflectors. Liverpool Philharmonic Hall is a modern hall having no separate reflector but a sloping ceiling above the orchestra and a flat reflector behind. There are splays on the side walls but since these contain the organ grilles they are probably not very efficient as reflectors.

In principle, the measurements were carried out by comparing the sound level at one omni-directional microphone close to the front row of seats at head height, with the level at other microphones mounted near head height close to the back row of seats, in the stalls and in the balcony or gallery. Two Philips tape recording machines were used to record the outputs of the two microphones for analysis in the laboratory. This method reduces the labour in the field and simplifies the relative calibration procedure of the two chains, while the material is retained in its original form and may be analysed in more than one way as circumstances suggest. Ideally this procedure would be best carried out with a twin-track recorder but a high quality machine of this type is not available at present.

The details of microphone positions necessarily varied from hall to hall but the usual arrangement was:

i. Front Microphone.

This was mounted on a microphone stand close to the conductor and between the platform and the front row of seats (as near to the latter as feasible) and at a height such that it was approximately in line with the orchestra as seen from the front row. The exception to this rule was in the Liverpool Philharmonic Hall, where the microphone was slung a few feet above the heads of the first row. This was necessary to allow free passage for the audience.

ii. Distant Microphone.

This was slung above a row near the back of the stalls or gallery, a few feet above the heads of the audience, except in the Usher Hall where it was secured to a ventilation grating at the back of the hall. The placing of the distant microphone is not as critical as the front microphone because it is in an area of reverberant sound; convenience of mounting therefore determined the exact position. In the case of the Free Trade Hall, which has a balcony as well as a gallery, separate cable runs to two distant microphone positions were provided, the microphone being transferred from one to the other during the interval in the public performance.

2.2. Recording Procedure.

The three microphone cables were led to a parallel terminal block and the output from the front microphone was fed permanently through a microphone amplifier to one recording machine. The input to the other machine through another microphone amplifier could be taken from either of the two distant microphones or from the front microphone in parallel with the first machine. Tone at microphone level could be fed from a tone source to the paralleled inputs to the two machines, and several frequencies were recorded at the beginning and end of each tape to provide a comparison between the relative overall frequency responses of the two machines. Tone at different frequencies was also used to provide cue marks and identification signals on the tapes. When an orchestral extract was recorded, the inputs were at first connected to the paralleled or common position and then, after a suitable period, the input of the second machine was connected first to one distant position and then to the other. The first part of the recording thus provided an additional check of the relative sensitivities of the two machines and their microphone amplifiers. The microphones themselves had been calibrated against each other and any correction for the differences in length of cable was allowed for in the subsequent analysis. This information was reinforced in some cases by an overall calibration provided by making recordings of pistol shots and piano music with all three microphones brought together in the hall, each on the same microphone cable as had been used for the measurements.

Judgement had to be exercised in choosing the passages of music for the measurements. The essential characteristics are that the music should be heavily scored and should have loud sustained passages. Some types of modern music are ideal

for this purpose. (A very good standby, although somewhat short, is provided by the National Anthem.) Passages with a single instrument predominating are not considered suitable, and this restriction sometimes made it difficult to find passages of sufficient length to allow adequate time for analysis.

3. ANALYSIS AND RESULTS.

3.1. Methods of Analysis.

Three methods of analysis were attempted:

(a) Both the distant and near microphone outputs were available by operation of a switch. An attenuator was placed in the near microphone circuit and adjusted until the levels from the two sources appeared identical to a listener.

(b) The outputs from the two sources were displayed on a double peak-programme-meter and an attenuator adjusted as before until the two needles gave the same reading.

(c) The two outputs were fed consecutively to a Brüel & Kjaer recorder.

The first of these methods is not suitable for octave analysis but provides a useful confirmation of the instrumental results. The second method was found to be inconvenient as the level differences between the microphones varied appreciably from moment to moment. For these reasons the third method was the one finally adopted.

The level recorder was set at its lowest writing speed, viz. 25 dB/sec. The circuit was arranged so that the outputs from the magnetic recorders could be fed either directly or through a bandpass filter with a bandwidth of one octave. The complete recording and analysis chain is shown in Fig. 1. The gain of the replay amplifiers was adjusted until the level of the recorded calibration tone was the same from both tapes which, for convenience, were usually played on separate machines, making any necessary adjustments for the frequency response. For each piece of music chosen for analysis, one of the tapes was played directly and then through octave filters covering a frequency range of 62 c/s to 8 kc/s. By running back the level recorder paper and using the synchronising tone recorded on the tape, the record from

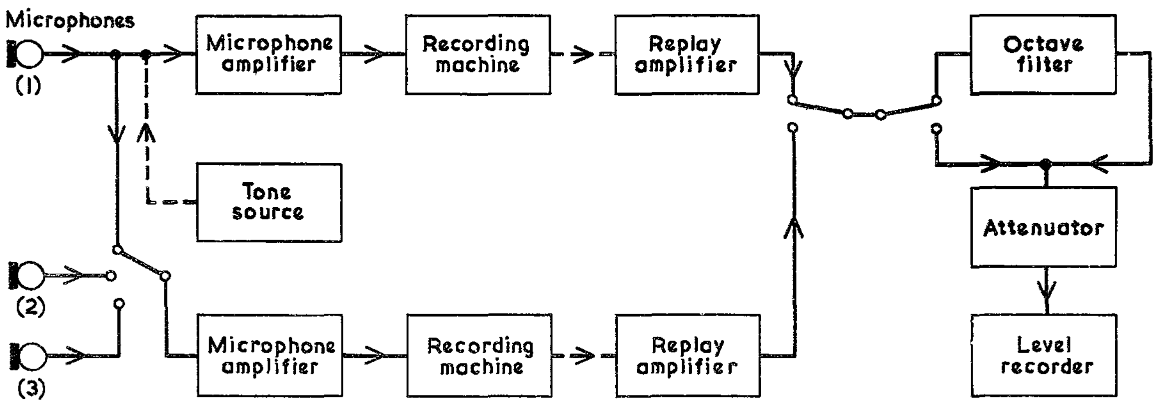

Fig. 1 - Recording and analysis chain

the second tape was arranged to coincide with that from the first for each filter position. An example of such a record is shown in Fig. 2. In most of the extracts analysed, the best records were obtained from the octaves with mid-points at 700 c/s and 1400 c/s. The relative levels were never entirely constant, presumably due to the movement of the effective position of the source. This was particularly noticeable in the lowest and highest octaves. A mean of several determinations was therefore taken in each case. As a rule, measurement was made from the general level rather than from the peaks of the recordings because the slow writing speed made suspect the records from the short peaks of sound. In fact, it was found that the measurement from the peaks usually gave a similar value to that from the mean.

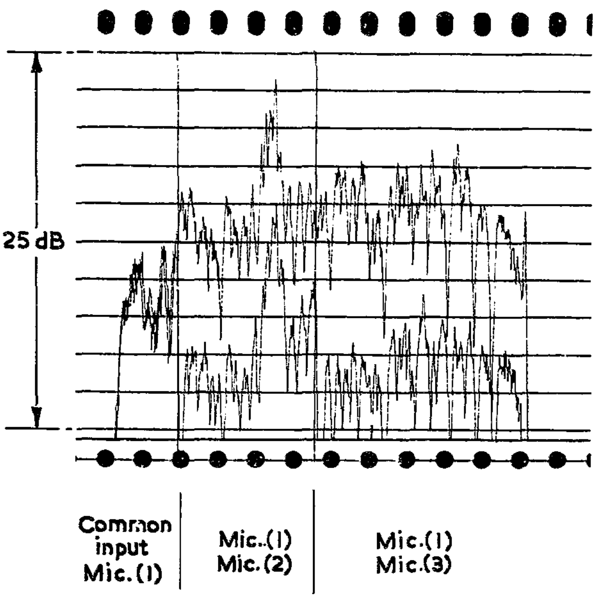

Fig. 2 - Typical level recorder trace
Writing speed 25 dB/sec
Length of extract 55 sec

3.2. Results.

The results are shown in a series of graphs in Figs. 3 to 11. Figs. 3 to 6 give the level differences for the five halls with an audience present, while Figs. 7 to 11 show the comparisons between the full and empty conditions. In the first set, the R.F.H. values have been used as a standard, being plotted with each of the other halls. (This procedure is adopted simply to facilitate comparison between the halls.) Measurements were not made in the balcony of the Usher Hall.

In Figs. 7 to 10, the stalls and balcony values are not plotted separately, the mean values being used so that the average effect of the audience is seen directly.

The results are summarised in Table 1, where a figure for each condition is arrived at, by taking the mean of the values for the two octaves from 250 c/s to 1 kc/s. This is admittedly a somewhat arbitrary method, but gives a fairer index for the hall, bearing in mind that the greater part of the energy will be in this frequency range. It is estimated that the average error of these results is of the order of ± 0·5 dB throughout.

TABLE 1

MEAN LEVEL DIFFERENCES IN dB (250 c/s – 1 kc/s)

	WITH AUDIENCE		NO AUDIENCE	
	Stalls	Balcony/Gallery	Stalls	Balcony
R.F.H.	9½	8	9	7½
F.T.H.	7	4½/6	4½	5
L.P.H.	6	9½	5	9
St. Andrews	7	6½	4½	4½
Usher Hall	8½	–	8½	–

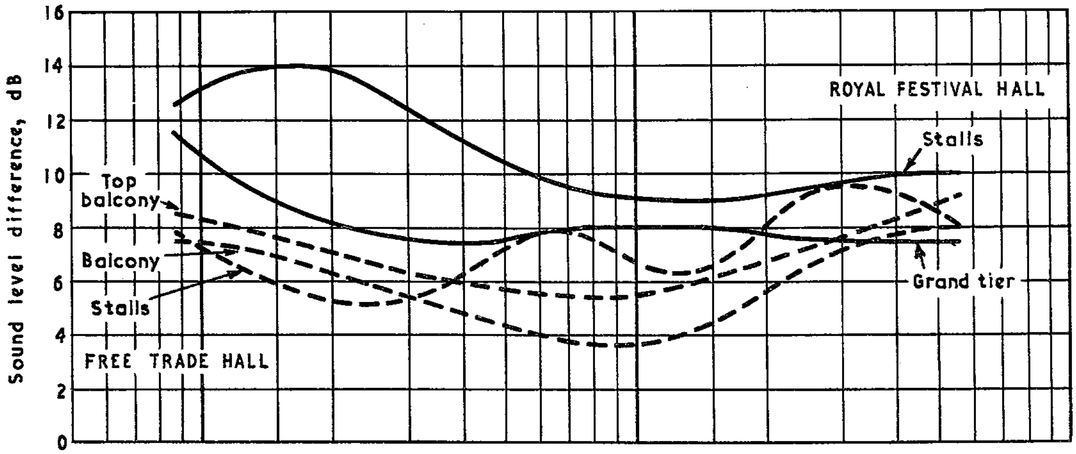

Fig. 3 - Sound level difference between front and rear seats
Free Trade Hall, Royal Festival Hall

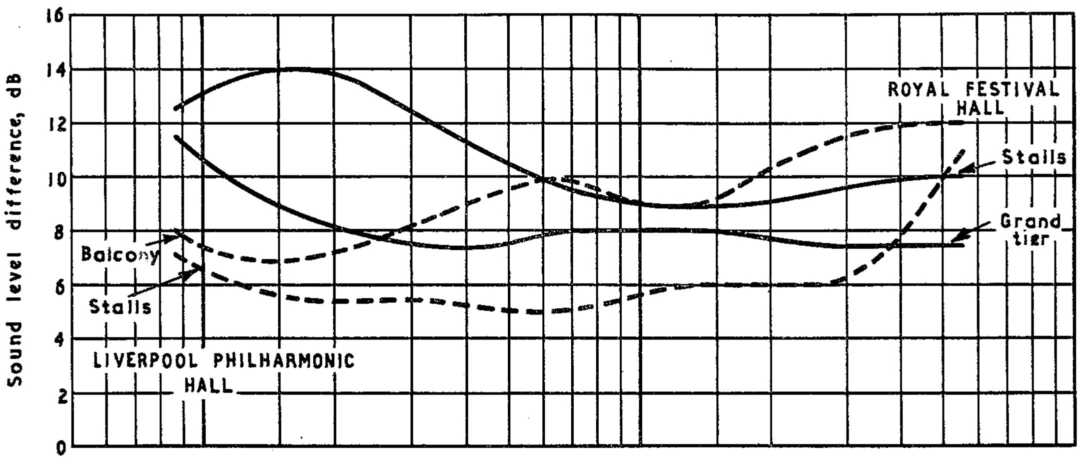

Fig. 4 - Sound level difference between front and rear seats
Liverpool Philharmonic Hall, Royal Festival Hall

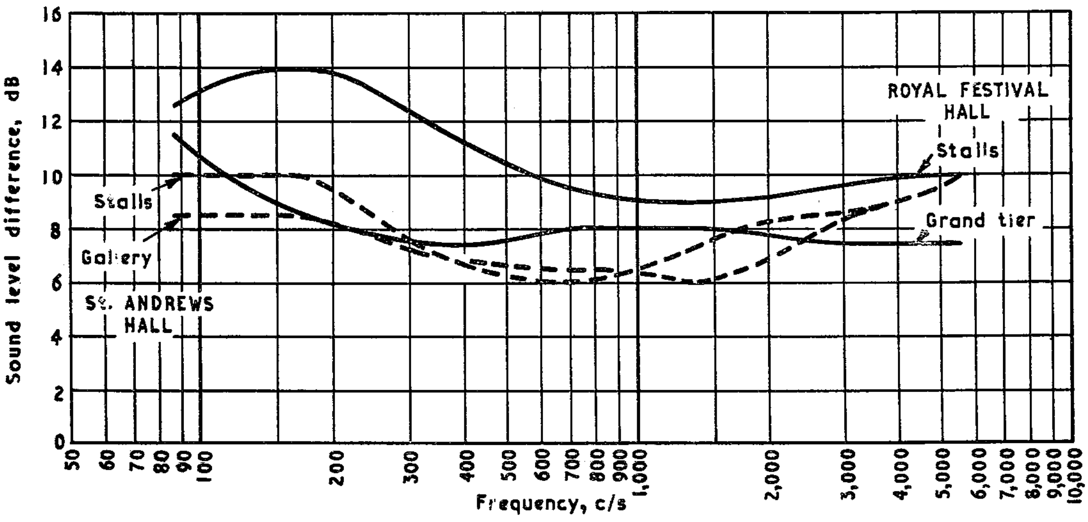

Fig. 5 - Sound level difference between front and rear seats
St. Andrews Hall, Royal Festival Hall

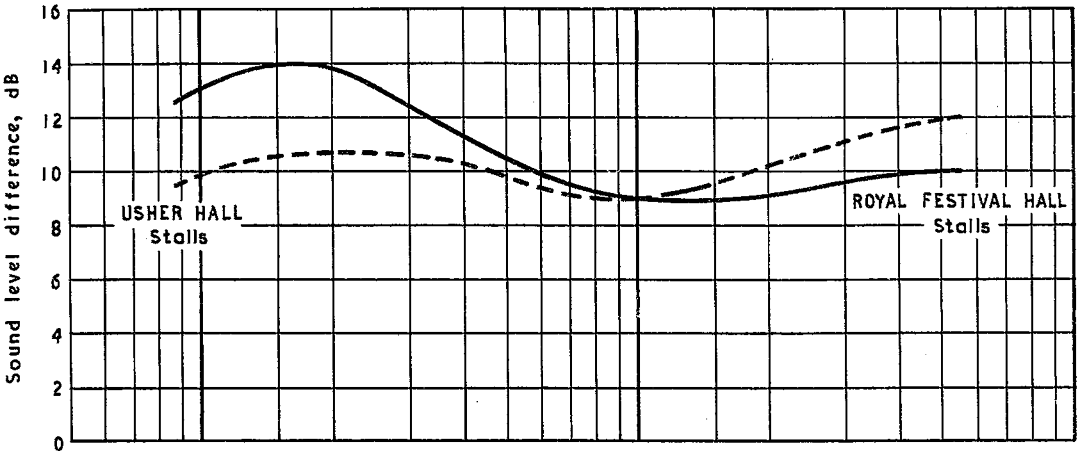

Fig. 6 - Sound level difference between front and rear seats
Usher Hall, Royal Festival Hall

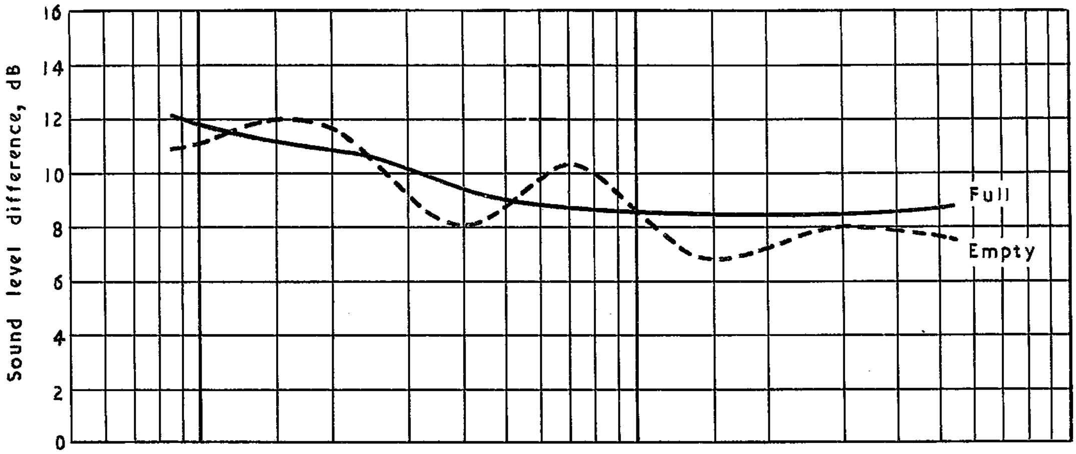

Fig. 7 - Sound level difference
Effect of audience, Royal Festival Hall

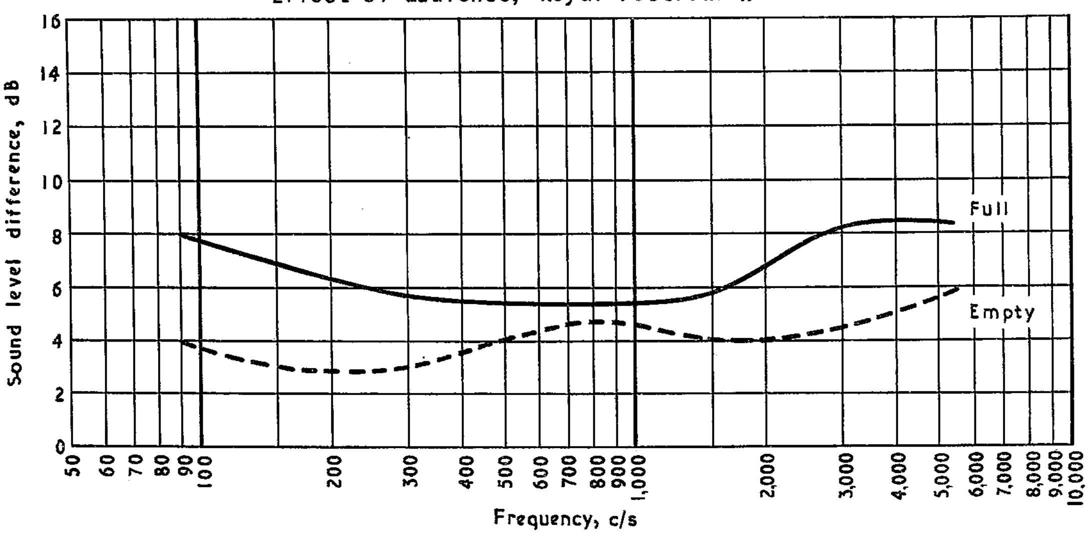

Fig. 8 - Sound level difference
Effect of audience, Free Trade Hall

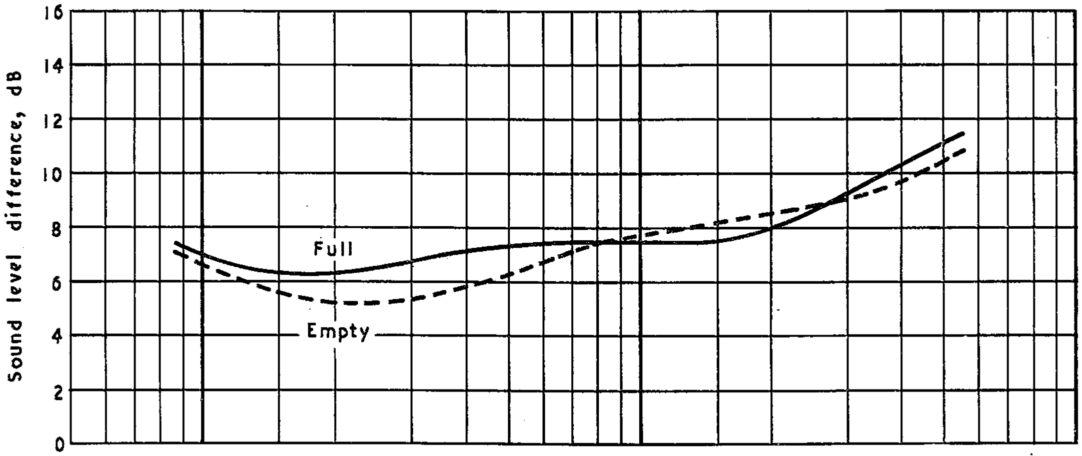

Fig. 9 - Sound level difference
Effect of audience, Liverpool Philharmonic Hall

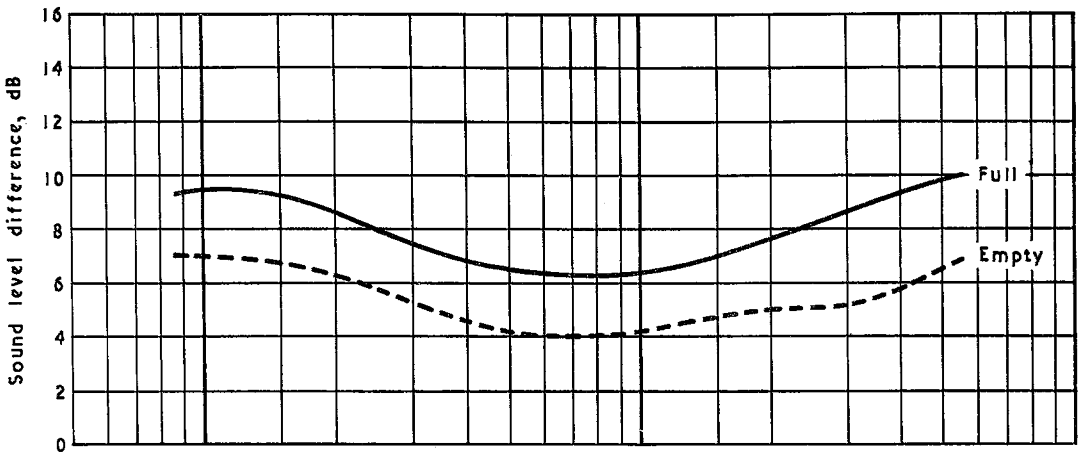

Fig. 10 - Sound level difference
Effect of audience, St. Andrews Hall

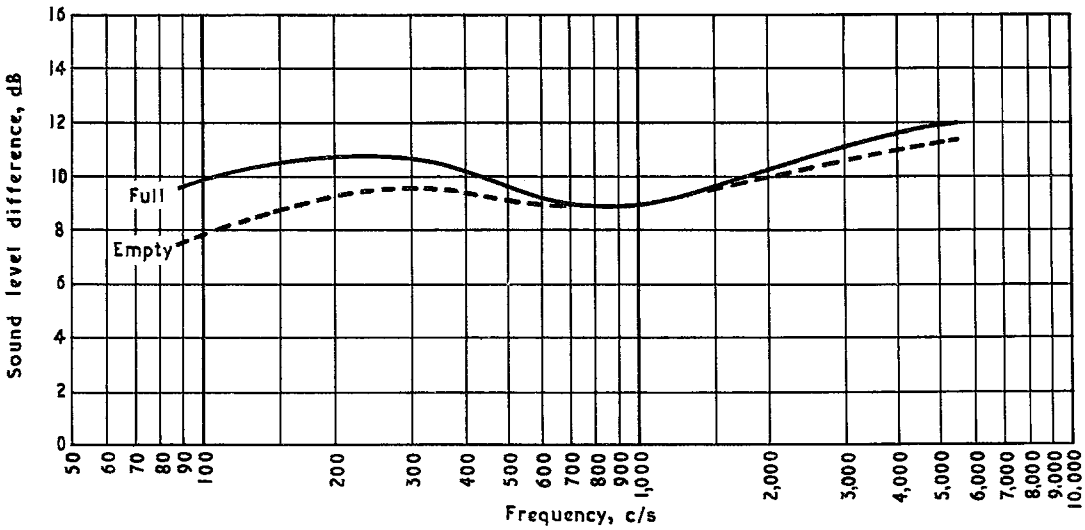

Fig. 11 - Sound level difference
Effect of audience, Usher Hall

On the whole there does not seem to be a great difference between the results from the various halls. The most notable exception is in the case of the Royal Festival Hall, where though the attenuation at the back of the grand tier is normal at low frequencies, that in the stalls is very large compared with other halls. This hall, it should be recalled, is the largest of those tested, and the microphone position here was well underneath the grand tier where listening conditions are known to be poor. It should be borne in mind, also, that the spread of readings in this frequency region is particularly large in this case. It will be seen that in the case of the Royal Festival Hall and the Free Trade Hall, the attenuation from the platform to the back of the stalls is greater than to the balcony. Although of a modern type, Liverpool Philharmonic Hall does not show this effect, probably because it is a smaller hall, and in particular, because the stalls do not extend under the balcony, so that there is thus a comparatively short and uninterrupted path to the platform. The large value for the balcony is presumably due to the very dead nature of this hall.

St. Andrew's Hall is notable in that there is no significant difference between the stalls and balcony positions; here, as with the Free Trade Hall, the height of the balcony above the heads of the audience in the stalls is greater than in the Royal Festival Hall. Referring to Figs. 7 to 11, it can be seen that there is no significant difference between the full and empty condition in the case of the Royal Festival Hall and the Liverpool Philharmonic Hall. In the St. Andrews Hall on the other hand, there is a difference of at least 2 dB through the whole frequency range and the Usher and Free Trade Halls show the same effect to a lesser extent. These results, in general, follow the pattern to be expected from the nature of the acoustic treatment of the different halls, as was mentioned in the introduction.

4. DISCUSSION.

These results show that the range of values to be expected in halls is not very great. There is no real evidence that the presence of a reflector reduces the attenuation from front to back in a concert hall. Certainly, the attenuation is small in the case of the balcony of the Free Trade Hall but on the other hand, it is large in the grand tier of the Royal Festival Hall. The large value for the back stalls of the Royal Festival Hall might be adduced as evidence that the reflector is having a pronounced effect in this hall; this is an area where the reflector is not visible and therefore, on the basis of ray theory, cannot be expected to be effective in increasing the direct sound. The effect is, however, most noticeable at low frequencies where the reflector would be least effective, and it therefore seems more likely that the result is due to the confined space in the back stalls. This area with its absorbent seats, carpet, and leather cushions and its wedge shape can be expected to be characterised by high attenuation.

It is probable that the results would be different if measurements could be made on the "direct" sound only. The true direct sound is hardly likely to be affected by the presence of a reflector, but the effective direct sound might be defined in one of two ways:

(1) to include all components reaching the listener within a certain time, say 50 ms, of the initiation or cessation of the original sound. This

includes first reflections from the side walls. There is great practical difficulty in measuring such short intervals of time with an orchestra due to the lack of perfect timing between the players and the time associated with the speaking of many of the instruments. For this reason also there is some doubt whether this concept of direct sound is subjectively valid.

(2) to include all components emanating from the general direction of the platform, so that the separation between the direct and reverberant energy could be made with a directional microphone. This definition is somewhat arbitrary, as some part of the reverberation process will be associated with the walls surrounding the platform. Nevertheless, an experiment to investigate this would be worthwhile. The difficulty in obtaining a microphone suitably directional at low frequencies and making arrangements for its use during a concert precluded the use of this technique in the present series of experiments. Meyer[2] has recently reported work in concert halls using a directional microphone.

The experiment described in this report is thus limited in scope, but in so far as level alone is important, it tells an important part of the story. Other factors than level have to be considered in studying the question of the presence or absence of a reflector. It may be, for example, that although a reverberant hall gives a reasonable value of attenuation without a reflector, some listeners may consider that the sense of intimacy or directness achieved is unsatisfactory and that a less reverberant hall would be more suitable; in this case it is quite possible that a reflector would be beneficial in replacing energy at the back of the hall lost by the reduced reverberation. This point cannot be investigated until a hall is available in which the reflector is removable.

In studying this problem, the fact that there is a considerable difference subjectively in using two ears to listen rather than one, (as in a simple microphone system) and the possible consequences of the Haas[3] effect, have to be taken into consideration. Both these factors may tend to produce a sense of directness, which may well be accentuated by a reflector. On the other hand, the preponderance of direct sound, the poorer diffusion in the region of the platform and the small apparent decrease of reverberation time following on the provision of a reflector causes, in the opinion of many observers, a deterioration in the tone quality of music played in the hall. The best compromise can only be established by subjective tests. It should, however, be borne in mind that there are in existence halls with a simple rectangular shape having adequate definition, tone-quality, and sound level distribution. (See Somerville[4], and Bagenal & Wood[5] in connection with this subject.)

5. CONCLUSIONS.

1. Steady state sound level differences between the front and back seats of halls of very different shape, with and without reflectors, are of the same order.

2. The original purpose in designing halls with reflectors in order to increase the sound level at the back, does not seem to be justified by the results.

3. These experiments have not taken into account the relative contributions of direct and reverberant sound. This is undoubtedly a relevant feature in discussing the effects of concert hall shape and it is possible that some people would prefer a higher ratio of direct to reverberant sound than others.

4. The evidence presented in this report fails to substantiate the claims made in favour of reflectors in concert halls. Bearing in mind that they appear to be a disadvantage in attaining the best tone quality, their use is therefore not recommended.

6. REFERENCES.

1. Parkin, "Some Objective Measurements in British Concert Halls", Report, (privately communicated) January 1950.

2. Meyer, "Definition and Diffusion in Rooms", Journal of the Acoustical Society of America, Vol. 26, No. 5, pp. 630-636, September 1954.

3. Haas, "Uber den Einfluss eines Einfachechos auf die Horsamkeit von Sprache", Acustica, Vol. 1, No. 2.

4. Somerville, "Subjective Appreciation of Concert Halls", B.B.C. Quarterly, Summer 1953, Vol. 8, pp. 121-126.

5. Bagenal & Wood, "Planning for Good Acoustics", Methuen, 1931.

APPENDIX

THE EFFECT OF A REFLECTOR ON THE SUBJECTIVE IMPRESSION OF REVERBERATION TIME

1. Apparent Reverberation Time.

The original definition of Reverberation Time, as used by Sabine, was the time taken, from the instant at which the source stopped, for the sound level to drop 60 dB from the initial level. The current practice, however, is to derive it from mean slope of the line obtained when the level (in decibels) of the reverberation sound is plotted against time. It is suggested, however, that in certain cases the apparent reverberation time, as appreciated by a listener, may be less than that derived from the mean slope, the difference depending on the relative levels of the direct and reverberant sounds, and the range of level which is appreciated by the listener.

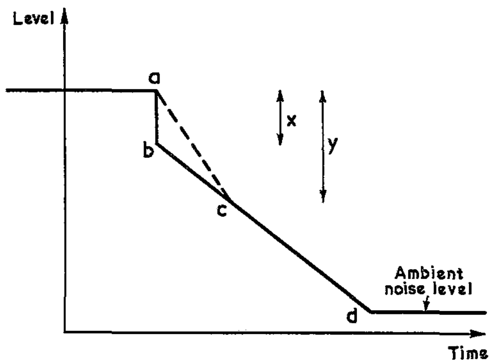

Fig. 12 - Apparent reverberation time

Fig. 12 shows an idealised decay with an initial drop of x dB after the cessation of the direct sound.

If we assume that the listener is only aware of a level range of y dB, it can be seen that the effective decay time, starting at the instant when the source is cut and ending when the level has dropped by y dB, is given by the line ac. The reverberation time as normally measured will be given by the line bd. In a concert hall the value of y may be determined by one of three factors:

(a) The threshold of hearing relative to the average level of the source.

(b) The ambient noise level relative to the average level of the source.

(c) The average time interval between successive sounds related to the reverberation time of the hall. The sound level from one particular initial sound will not have time to decay beyond a certain value before the next sound is heard.

Of these three, the factor which gives the smallest level difference will determine the value of y. In practice factors (b) and (c) will give smaller differences than (a), and the relative importance of these two will vary from moment to moment. When the source is an orchestra (c) will normally be the important factor except at the end of a phrase or when discrete chords or notes are played with appreciable intervals between.

A value of 30 dB for y was initially thought to be reasonable, but Brüel[6] suggests that a value as low as 10 dB may be more appropriate for orchestral music. Several possible values are considered in the calculations below.

For any one value of y the difference between the apparent reverberation time and the measured quantity will depend on the average value of x.

An approximate treatment has been used to compute the order of magnitude of the difference between the measured and apparent reverberation times, and the effect of a reflector on this difference.

2. Effect of a Reflector.

It was assumed that all sound that falls at any time directly on to the audience can be considered as completely absorbed and is therefore lost to the reverberation process. The remainder of the sound energy is in general reflected from the walls of the hall and afterwards suffers a large number of reflections from surfaces having very different absorption coefficients. Some of the sound will fall on the audience and be completely absorbed. It is this process which determines the average absorption coefficient, and hence the reverberation time. When a reflector is present a greater proportion of the initial sound energy is directed immediately on to the audience and consequently the reverberant energy is reduced.

The influence of the reflector may be estimated by considering the solid angles subtended by the audience at the source directly in one case and by its "image" in the reflector in the second. These angles were computed approximately.

Assume that the source normally radiates into a solid angle of 2π, that is into a hemisphere. Let the total solid angle subtended directly by the audience or by the image of the audience in the reflector be θ. Then the reverberant energy level, which can be considered as constant throughout the auditorium, will be proportional to the angle $(2\pi - \theta)$.

The direct energy will, however, be dependent on the distance of the listener from the source; it will be increased by the reflector by an amount that will not exceed the direct energy level.

3. Calculation and Results.

The initial drop is equal to the ratio, expressed in decibels, of the direct to reverberant sound energy. The direct level for a seat in the stalls, at the average distance for all seats from the platform, was calculated using the inverse square law. It was compared with the reverberant energy level computed using the concept of energy density which leads to the Sabine reverberation formula. The reflector was assumed to have a reflection coefficient of unity.

As an example, the approximate values of effective reverberation time computed in this way for a typical hall with an actual reverberation time of 1·5 sec are given in the table:

Effective Level Rangle (y)	Apparent rev. time (no reflector)	Apparent rev. time (reflector)
10 dB	1·37 sec	1·24 sec
20 dB	1·45 sec	1·36 sec
30 dB	1·47 sec	1·41 sec
60 dB	1·48 sec	1·45 sec

The figures in this table show that whereas a reflector has little effect on the true reverberation time of the hall, the apparent reverberation time measured during a small change from the initial level is substantially reduced. This may explain the decrease in the subjective liveness noticed when the conditions are such that only a small range of level is heard by the listener, for example in quiet continuous orchestral passages or staccato playing where the later stages of the decays are masked by succeeding notes.

4. Reference.

G. Brüel, "Sound Insulation & Room Acoustics", London, Chapman & Hall, 1950, p. 175.